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Paradigm shift in U.S. space policy

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ESA's Gravity Field and Steady-State Ocean Circulation Explorer satellite is yielding discoveries in the Earth's interior and what it reveals about volcanoes and earthquakes. The satellite's mission

Making the most of GOCE

SOMETIMES A SPACE PROGRAM'S CAPABILITIES change significantly because the operating environment turns out to be markedly different from the model used in designing the mission. When this happens, it usually is bad news for all involved. A spectacular exception is ESA's GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) satellite.

Launched from northern Russia on March 17, 2009, GOCE was expected to spend 20 months orbiting at the very edge of the atmosphere, studying the Earth's gravity field and its variations. Mission models had called for six months of measurements, to be followed by four months of "hibernation" while the satellite was in a period of eclipse, then six more months of measurements. ESA hoped that the mission's life might be extended enough for an additional measurement phase if on-board fuel reserves were not depleted by orbital adjustments.

But two developments have now given researchers far more time for measurements than they ever thought possible—an extremely precise initial orbital placement and discovering that the hibernation period will not be necessary. (See "GOCE adds gravity to

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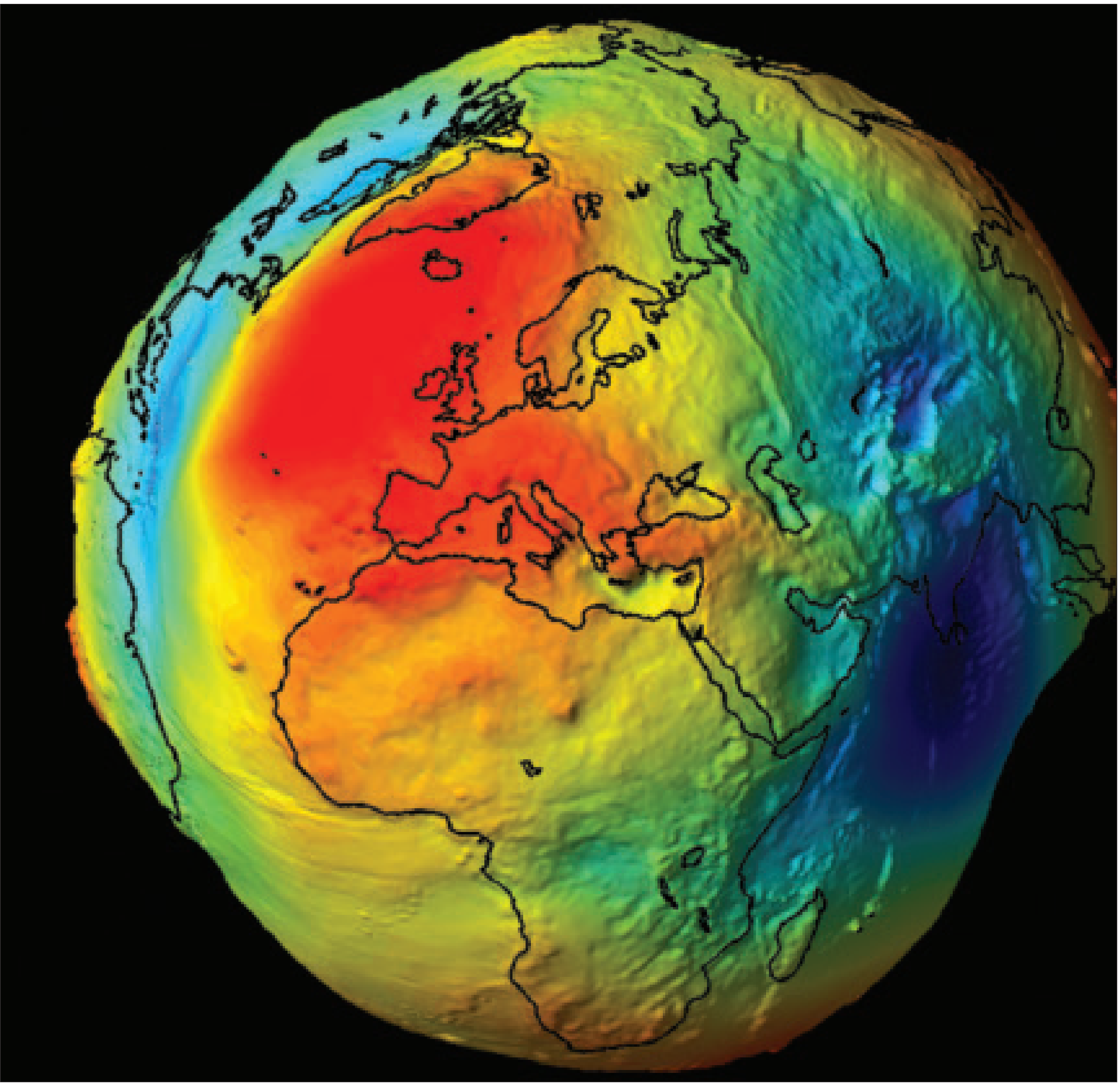
areas ranging from ocean currents and their effects on climate to the density of is also gaining significant benefits from some surprising on-orbit conditions.



The GOCE mission is measuring high-accuracy gravity gradients and providing a global model of Earth's gravity field and of the geoid. The geoid (the surface of equal gravitational potential of a hypothetical ocean at rest) serves as the classical reference for all topographical features. The accuracy of its determination is important for surveying and geodesy, and in studies of Earth interior processes, ocean circulation, ice motion and sea-level change. Credit: ESA.

ESA's agenda," July-August 2009, page 32.)

"We have funding for the program until the end of the nominal mission, which is April 2011, but it is clear we have resources on board for a longer mission," GOCE mission manager Rune Floberghagen tells *Aerospace America*. "When we launched, we knew solar activity was low, but the type of air drag we encountered in the 280-km injection orbit was really remarkable, about a factor 4-6 less than any model we had been using.

"There are two reasons for that—one, solar activity is low, so actual air density is much less than we had designed for; second, the interaction between the satellite and the environment was different from any models we had devised. The way of modeling the upper layers of the atmosphere, whether using a thermal or a rarified gas model, suddenly was very different from what we experienced. For science, that is good, meaning we can fly the mission lower than anticipated, and the delay in launch from the original plans [May 2008] hasn't hurt us at all."

Learning to fly

The GOCE satellite relies on aerodynamic passive stabilization. Operating in an environment unlike that for which the attitude controllers were designed did cause some early problems with these devices, but the overall impact was stunningly positive.

"The first thing we had to learn was how to fly the satellite—which has a long, thin design very different from the typical 'washing machine' style—in this very much reduced air drag environment. Once we got that under control, however, it was excellent news for the mission," he says. "We have been moving steadily lower in the atmosphere as a result and currently are at about 254.9 km, which is excellent for signal-to-noise, which is better for the mission."

Floberghagen and his team spent the better part of the summer of 2009 "basically doing nothing much else than letting the satellite decay freely down to an altitude where the air drag is within the envelope of the ion engine—air levels between 1 and 20 millinewtons," he adds. "What we saw in the injection altitude is that for about one-third of each orbital revolution, there was basically no air at all, less than half a millinewton.

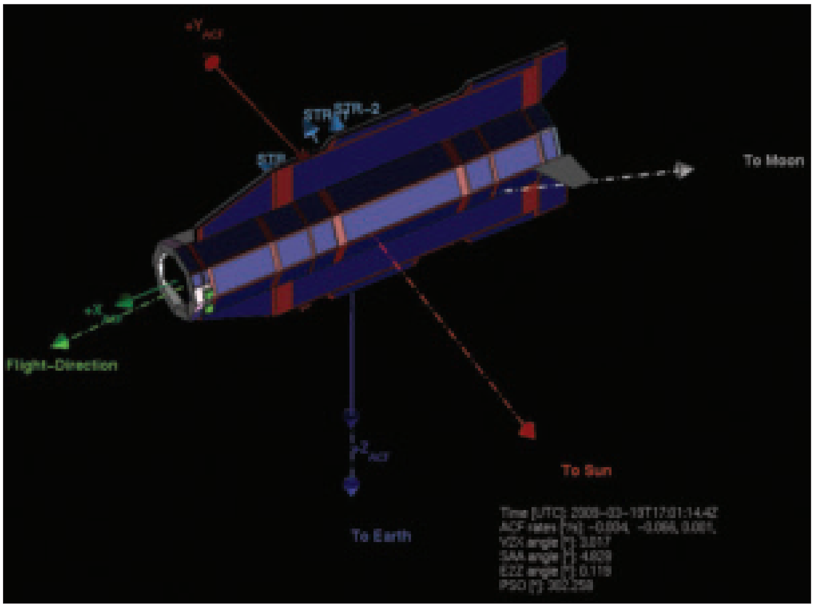
"For up to half an hour of every 90-min orbit, we had air drag well below the minimum capability of the engine, allowing it to overcompensate at a steady level of operation. The orbit altitude then increases a little and measurements become better. We could fly below 250 km, but it takes time to dive through the atmosphere, even when there is so little. We decided 979 orbital revolutions in 61 days was a good orbit with decent noise and excellent sampling capability, so we stopped the decay and started the science phase," Floberghagen says.

To ensure constant sampling characteristics for the gravity field, the satellite's altitude is actively maintained to within ±50 m, far more precise than the 1-km altitude control requirements in the mission plan. In reality, Floberghagen says, they have been able to keep the satellite within a couple of meters of its target altitude on a steady basis.

"That means the system is working in a predictable way. The ion propulsion system is coupled to a controller using satellite instruments to measure all the forces that act on the spacecraft. A control signal then goes to the engine, so the system works in a closed loop," he explains. "So the altitude goes up or down depending on whether the bias of the system is plus or minus.

"Our drag-free and attitude control system does not only maintain the altitude, but makes sure it is free from any environmental perturbations, so the sensor flies as if it is in a complete vacuum. And the system has reduced this very low air drag by at least three orders of magnitude. In fact, the drag-free system is operating at least one order of magnitude better than spec, so even as a technology demonstrator, GOCE is a fabulous success."

This screenshot was taken from the Flight Dynamics system and shows GOCE oriented in orbit after achieving Fine Pointing Mode. The two green arrows pointing to the left are aligned, indicating that the spacecraft is properly oriented along the direction of flight, thus minimizing drag. Credit: ESA.

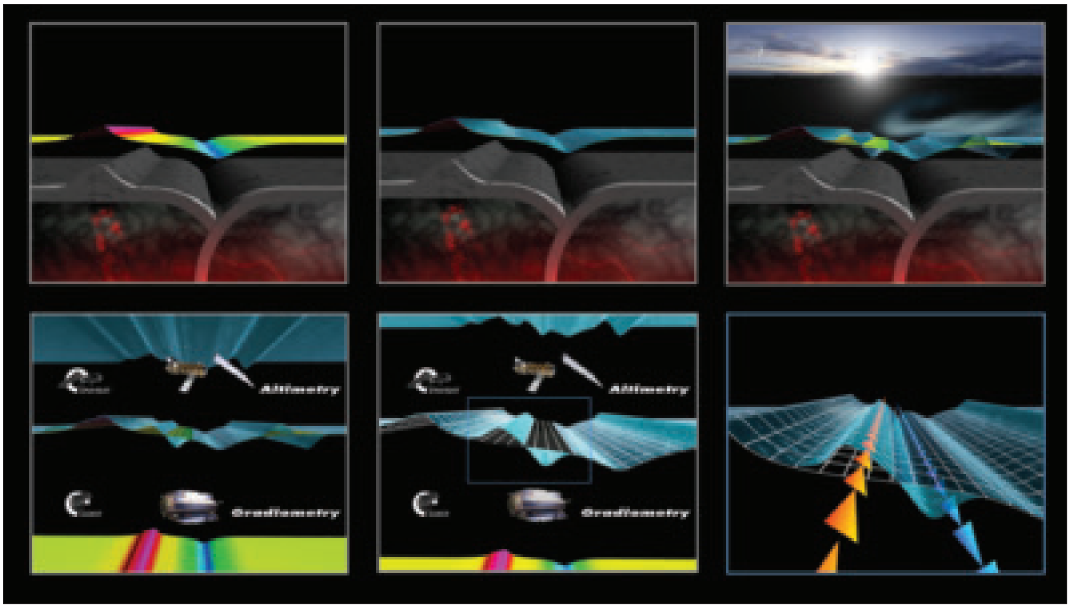


A matter of gravity

The technologies used in the satellite are not the only successes, however. Floberghagen says the data they have collected in just a few months of operation have greatly expanded knowledge of the Earth's gravity. Once a complete plot has been created, it will have implications for everything from bridge construction to space launch sites.

"GOCE sees geophysical phenomena that have hitherto been hidden in previous gravity field measurements. They constitute the proof that GOCE data will definitely set a new standard in the modeling of the gravity field—and therefore in the use of gravity field models in all related areas of the geophysical sciences," he says.

"The big number-crunching job that lies ahead of us is to turn these 'maps' of measurements into a gravity field model showing the geoid or, indeed, the value of '*g*' everywhere on Earth." (The geoid is the irregular gravity field that shapes a virtual surface at mean sea level.) "This will be done in the coming few months. Presentation of our first grav-



Density variations in the Earth's crust are an important factor in shaping the geoid. External forces such as the wind cause the actual sea surface to deviate from the geoid. The combination of sea-surface height mapped by altimeters and the knowledge of the precise ocean geoid will improve our understanding of surface currents.
Credits: ESA - AOES Medialab.

ity field model is expected in June."

The initial months of calibrated measurements have followed predicted existing global gravity field models, but also have shown high spatial resolution variations, he says. The amount of variation depends on the area being observed; those already well surveyed using gravitometers on the ground or airborne data show strong correspondence, and regions not as well surveyed show greater differences, resulting in models based on previously imprecise data.

"Now we are trying to use these measurements to determine the underlying force field parameters and the geoid. That is now just getting started, but we are confident the results will be quite spectacular," Floberghagen predicts. "So far nothing hugely unusual has been seen, although we have seen things moving around a bit with respect to previous models, on a spatial scale of a few hundred kilometers, not really that small.

"But that could be the result of our initial data processing, or varying rock densities, or what is inside those rocks. We really need to take a close look at all those things before saying anything definitive. There are high-frequency spatial variations we will be investigating one by one, but it is a bit early to draw any conclusions. In six months we will know much more," he continues.

Keeping quiet

Not having to put the spacecraft into hibernation for four months at the end of each measurement cycle means the satellite can operate in full measurement mode throughout the life of the mission.

"Of course, while traveling through the eclipse, we will have to understand and deal with temperature variations, because when the satellite goes from full sunlight into complete darkness and back again, there may be some thermalastic results. You could have small amounts of stress or buckling of the solar panel that would produce small vibrations—micrometer-per-second acceleration," notes Floberghagen. "If you have a sheet of thermal insulator about 5x5 cm and it moves a millimeter at 1 *g*, you would induce acceleration on the satellite by six orders of magnitude above the sensitivity of the instruments.

"So it is of paramount importance that the environment aboard the satellite is extremely quiet, which is why we have no moving parts and attitude control is done by magnetic torquers. There are lots of factors in place to reduce any movement or noise, but we cannot exclude some response in the structure of the satellite and main instruments to these [temperature] variations. However, these effects so far have been few and far apart, so we don't believe we will be much hampered by them. Which means not only do we have the power to operate through the

"Based on careful estimates, we now believe we have enough resources to keep the mission flying for five years or so."
Rune Floberghagen, GOCE mission manager, ESA

GOCE will significantly advance our understanding of the physics and dynamics of the Earth's interior such as volcanism. Its detailed mapping along with seismic data is expected to shed new light on the processes causing earthquakes and volcanic activity and potentially lead to an improvement in the prediction of such events.

eclipse phase, we also believe the measurements, if not exactly as accurate as during the normal phase, still will be excellent."

Asking the right questions

With only a few months of measurements completed, it is still too early for GOCE to begin addressing some of the major questions scientists hope to examine. These range from using a uniform, global measurement of sea levels for studying ocean currents and thus improving climate models to providing more precise information about Earth's interior, from magma flows to tectonic movement, which could give geophysicists greater knowledge of volcanoes and earthquakes.

"We believe we will be able to meet all the original objectives of the mission. What that means in terms of how well we can measure cubic liters or kilometers of water circulating in specific areas of the oceans, we haven't gotten that far yet. It will be at least a year longer before we can begin doing that,"says Floberghagen.

"But when we look at the mission and performance results so far, we don't have to filter the data to get rid of striping effects or anything; it is all straight out of the box. If that also is the case later on for the gravity fields and oceanographers, it will truly be successful. But you have to gradually build a picture and do a lot of number crunching before you actually understand what all those pixels mean."

Studying the oceans—and below…

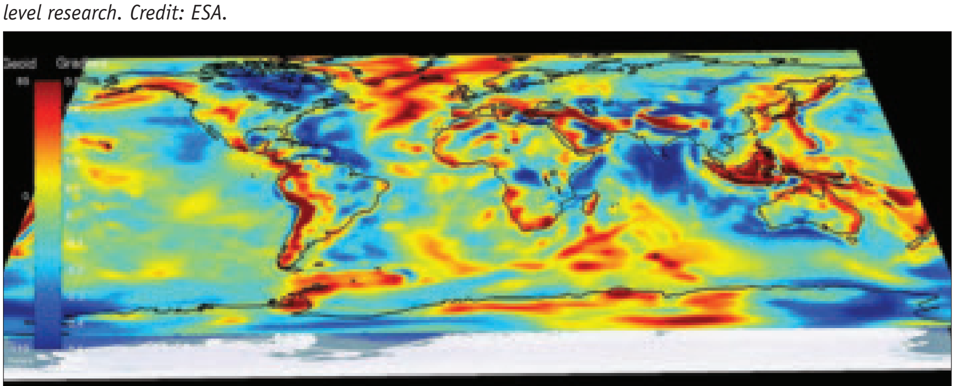
Outside of its demonstration of new methods of construction, propulsion, attitude control and edge-of-the-atmosphere flight, determining the impact of gravity variations on ocean currents remains the area in which GOCE is expected to have the greatest scientific impact. That has become even more important in light of new controversies surrounding the legitimacy of past global warming research and models.

"Given the whole debate about climate change, a uniform height system for the world, based on gravity and a uniform-quality gravity field, will allow us to revisit all the tidal records from around the globe—for the past 200 years in many places—and study sea-level rise and climate change as it impacted ocean height, in a way that has not been possible before," Floberghagen points out. "However, the data GOCE provides must be combined with other data sources to draw any meaningful conclusions with regard to climate.

"For example, we provide a reference service on ocean levels and deviations. But you need to reprocess 20 years of altimeter readings using the new data from GOCE to better determine ocean behavior during that period. Oceans truly are the planet's climate regulators, with most heat transferred through atmosphere-ocean interaction. But we need to determine the geoid, reprocess all the altimeter sets, assimilate that into ocean models and then into climate models. So we can't just measure gravity fields for a couple of months and then declare we have new knowledge about climate."

The scientific interest in GOCE's results extends far beyond those involved in studying climate, however, including what is happening beneath the surface.

"The higher the density of the planet's core, the higher the level of gravity. If density distribution were regular, we would not be able to see the differences between various layers simply from looking at surface



GOCE's final gravity map and model of the geoid will provide well-defined data products that will be instrumental in advancing science and applications in a broad range of disciplines from geodesy, geophysics and surveying to oceanography and sea-level research. Credit: ESA.

data. However, if the core deviates significantly from regular distribution, that would influence Earth's rotation—and there is a direct relationship between Earth rotation and gravity," he says.

"But more important for gravity is what happens closer to the crust, such as the mantle and temporal variations. So aside from the mean value of gravity, which is largely determined by the heavier material in the Earth's core, the variations are the result of things that happen closer to the surface. Which is why we can see plate tectonic changes in the gravity data, for example."

Having GOCE in orbit and making measurements for at least five years, rather than the originally planned 20 months, also will provide greater opportunities to measure, in real time, the impact of any future major geological events. The Sumatra earthquake in 2005, for example, led to a vertical displacement of several meters in a large section of the ocean floor. The result, Floberghagen says, was a measurable change in the Earth's rotation—the length of a day.

"Even an instant phenomenon, such as an earthquake, in geological timescales, can influence the Earth's rotation speed. And if something like that happens during the lifetime of the GOCE program, we certainly could see and measure that in our data," he notes. "A theory based on such data from a big event and applied to events that happened hundreds or millions of years ago would not be completely out of reality, but it would be difficult to put truly quantitative data on that.

"We're trying to combine all the information we can get, but looking inside the Earth is pretty hard to do. You try to combine gravity, magnetic field information, data on seismic wave travel times and so on to deduce something about an event. Gravity field information adds to that, and gravity has a tendency to restrain the others. But if you know and understand better what might happen, you can better prepare yourself."

...and the air up there

A new and serendipitous mission goal is to improve scientific understanding of air density by looking at air-drag models of the thermosphere through which the satellite is flying.

"Because our data are very different from what the models predicted, we are looking at addressing air density and winds in an orbital altitude where no one else has flown," notes Floberghagen. "We should not just leave what we've found on that in the drawer, but make it available to build better models of the atmosphere at this altitude. That is a byproduct we are 90% sure we can produce in the next couple of years."

That element not only has increased the potential value of the GOCE mission, but also is expected to impact the entire family of European Earth explorer satellites, of which GOCE is a member. Six essentially single-issue satellites are being built to examine fundamental Earth science, from gravity to clouds and aerosols, thermal issues, the magnetic field, sea ice and so on. A seventh satellite is under study, and ESA has called for ideas for an eighth.

An accurate model of the geoid will advance our understanding global ocean circulation patterns and sea-level rise.

Deciding what's next

"One discussion now running within ESA is what to do with the knowledge we are gaining from GOCE and other early satellites. We have two branches of Earth observation missions in ESA: The workhorses, such as Global Monitoring for the Environment and Security, which are closely linked to the activities of the EU and the theme of the Earth observation mission; the other is doing things that have never been done before, more along the lines of invention and exploration," he explains. "But after we have done the first generation of explorers, then what?

"In Europe, you can propose to build another Earth explorer, addressing new elements learned from the first. But is that enough? There may be follow-on missions arising from different satellites. For example, an operations agency might be interested in picking up the torch to do weather forecasting because of information gathered from a first-generation satellite, so discussions with operating agencies are being held on all the Earth explorer satellites. But you also have very scientific elements, where it might not be possible to fly a next-gen immediately after the first, because the first generation already was pushing the limits of technology. At this point, we really don't know what may arise in that area."

In addition to processing information this satellite is gathering, therefore, the GOCE team also must begin putting together a clear and precise report on what has been learned in terms of technological challenges to building, launching and flying the satellite, whether it was worth the investment and whether future missions along the same line should be considered. Such evaluations also could significantly impact the future of international cooperation and new joint missions.

"It has been a great decade for geopotential research, from GRACE [Gravity Recovery And Climate Experiment, a five-year, twin-satellite joint effort by NASA and the German space agency] to GOCE. Gravity field missions have the potential of measuring variations in the Earth's mass, whether in time or space, and people want to capitalize on that and build a platform to monitor this over longer time periods in the future," Floberghagen says. "In the U.S., a GRACE follow-on is part of Tier 3 of NASA's decadal survey, and in Europe there is significant pressure for a next generation of gravity field missions.

"The idea would be to combine the capabilities of GRACE, in terms of temporal resolution, with GOCE, in terms of spatial resolution, to measure variations in the Earth system, from ground water changes to ice floes to temperature variations. We don't know what will be the ultimate conclusion of all this, but international cooperation for the next-generation missions certainly is possible, given the technology, scientific expertise and interest on both sides of the Atlantic."